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# REPORT ON THE EVALUATION OF TWO PROTOTYPE CHEMICAL PROTECTIVE CLOTHING GARMENTS



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# TECHNICAL REPORT

# REPORT ON THE EVALUATION OF TWO PROTOTYPE CHEMICAL PROTECTIVE CLOTHING GARMENTS

by

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13. ABSTRACT *(Maximum 200 words)*
The study evaluated the heat strain experienced by seven soldiers exposed to heat stress while exercising in prototype and issue chemical protective (CP) garments in Mission Oriented Protective Posture (MOPP-1). The control garments were the issue Chemical Protective Undergarment (CPU) and Marine Saratoga Overgarment (CPO). The prototype (X) garments were lightweight CPO and CPUs. Testing consisted of 100 min exposures to thermoneutral (20C, 50% RH), desert (49C, 20% RH) and tropic (35C, 75% RH) environments while walking at 1.34 m·s-1 (3 mph). Data included rectal temperatures and total endurance times (ET). In descending order of performance, the results indicate a joint ranking of the two overgarments, then the prototype undergarment (CPU-X) and, finally, the issue undergarment (CPU-C). One significant difference between the two overgarments indicated an advantage for the prototype (CPO-X), whereas other observations indicated that the issue overgarment (CPO-C) was a more "wearable" garment. The issue undergarment (CPU-C) was significantly different (worse) than the two overgarments. In fewer cases (49C), the prototype undergarment (CPU-X) did significantly worse than the overgarments. Between the two undergarments, all significant differences indicated that the prototype (CPU-X) would induce less thermal strain than the issue (CPU-C) undergarment.

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## DISCLAIMER



Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on Use of Volunteers in Research.

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This study was funded by the Natick Research, Development and Engineering Center (NRDEC). We would like to acknowledge the assistance of Mr. T. Pease and Ms. S. Seasholtz from that organization. Protocols involving the use of human volunteers as test subjects require the involvement of a large staff. The authors would like to acknowledge the contributions of the following individuals who assisted in the protocol: K.R. Schafer and W.F. Allison. We would also like to thank Ms. D.M. Danielski for assistance with the manuscript and Ms. L.L. Lameka for assistance with the recruitment of test subjects. Finally, we would like to thank our volunteer test subjects, whose participation made this study possible.

# EXECUTIVE SUMMARY

The purpose of this study was to determine if new prototype chemical protective (CP) clothing reduced heat strain relative to issue CP clothing. The study evaluated the heat strain experienced by volunteer test subjects exposed to heat stress while exercising in prototype CP garments in a modified Mission Oriented Protective Posture (MOPP-1) configuration. Two issue garments, the Chemical Protective Undergarment (CPU) and the Marine Saratoga Overgarment (CPO), were the control (C) garments. The prototype (X) garments were lightweight CPO and CPUs. The undergarments were worn with the U.S. Army Battledress Uniform (BDU). Seven volunteer test subjects walked on treadmills in a modified MOPP-1 level of chemical protection while wearing the test garments. Volunteers wore the integral hood and CP gloves during all testing in thermoneutral (20°C, 50% RH), Desert (49°C, 20% RH) and Tropic (35°C, 75% RH) environments while walking on a level treadmill at 1.34 $m \cdot s^{-1}$ (3 mph) for 100 minutes. Data included rectal temperature, three skin surface temperatures, volunteer exposure or tolerance times and heart rate. The total length of the study was 19 days, including 6 days of acclimation, 12 days of chamber testing, and 1 make-up session.

As noted above, "C" designates the issue or control garments and "X" the experimental or prototype lightweight garments. The data indicate a ranking of the CP garments of the two overgarments, then the prototype undergarment (CPU-X) and, finally, the issue undergarment (CPU-C) in descending order of overall performance. The only significant differences between the two overgarments were found for a contributing factor (evaporative water loss) in the least stressful environment. There was contradictory and non-significant data for endurance time (ET) that suggested that the issue overgarment (CPO-C) was a more "wearable" garment than the prototype overgarment (CPO-X). Consequently, any thermal advantage of OX over OC is rather tenuous. The issue undergarment (CPU-C) was significantly different (worse) than the two overgarments. In fewer cases (49°C), the prototype undergarment (UX) did significantly worse than the overgarments. Between the two undergarments, all significant differences indicated that the prototype (CPU-X) would induce less thermal strain than the issue (CPU-C) undergarment. When there were statistically significant differences between the undergarments, the prototype (CPU-X) tended to perform better than the issue undergarment.

# I. INTRODUCTION

## A. PURPOSE

The purpose of this study was to evaluate prototype Chemical Protective (CP) materials for wear by Army personnel during warm weather operations. More specifically, this study quantified the physiological responses of volunteer test subjects performing moderate exercise during exposure to heat stress while wearing issue and prototype CP overgarments in a modified Mission Oriented Protective Posture (MOPP-1) configuration. The data were to be used to evaluate prototype garments for possible further development rather than a final comparative study to select an issue garment. Individual data collected included rectal temperature, three skin surface temperatures, subject endurance times and heart rate. The basic objective of the study was to provide the sponsoring agency, Natick Research, Development and Engineering Center (NRDEC), with sufficient data to compare two prototype garments to the existing CP garments and to provide information for the selection of CP prototypes for further development and possible procurement.

## B. MILITARY RELEVANCE

Even the threat of chemical weapons can subject opposition forces to the encumbrance of CP ensembles. The reduction in soldier performance is exacerbated when soldiers are exposed to additional stress due to heat exposure during exercise. The twin goals of minimizing heat strain while providing protection against chemical and biological agents is a basic concern in the development of CP garments and ensembles. These tests will provide an indication of the relative performance of soldiers while wearing issue and prototype garments in hot-dry (desert), warm-humid (tropic) and temperate climates.

## C. BACKGROUND

### 1. Previous Studies

Military and defense industry literature (4,12,13,25) indicates the importance of CP clothing in modern military operations and reinforces an awareness that CP clothing impairs effective soldier performance during heat stress. Although many factors influence the selection of CP clothing, the physiological strain experienced by soldiers wearing CP clothing is a significant factor in performance degradation. The specific objective is to determine if new CP clothing offers an advantage by reducing heat strain, relative to other CP clothing, including both standard issue and other prototypes. Other recent human studies of CP clothing include those of Vallerand et al. (28), McLellan et al. (17,18,19), Bomalaski and Constable (2,3), and Allsopp and Pethybridge (1). Papers on the evaluation of permeable CP clothing from USARIEM include Gonzalez et al. (11), Santee and Wenger (24), and Santee et al. (22). USARIEM Technical Reports generated from the TTCP program include TR94-4, TR94-12, TR95-10, TR95-14, TR95-16, TR95-17, TR95-18.

Numerous scientific studies (6,7,8,14,15,21,26) have established that CP clothing degrades soldier performance. A primary cause of this degradation is an increase in heat strain, which is incurred because CP clothing reduces heat loss to the environment. In a "warm" environment, the metabolic heat generated by an individual is often in excess of the quantity required to maintain homeostasis. Unless excess heat is transferred to the environment, an imbalance will occur, the body core will begin to warm, and the increasing level of thermal strain will affect performance. Clothing impacts heat exchange between a body and the environment by altering the rate of heat transfer by mechanisms of "wet" and "dry" heat transfer.

## 2. Thermal Factors

There are several factors that interact to determine the heat exchange between an individual and his environment. One factor is the environment. Environmental factors include the temperatures of the air and any surfaces in contact with the individual, air movement, radiation and humidity. An additional factor is the individual. Significant physical characteristics are mass and surface area. Significant physiological characteristics include body temperatures, activity (metabolism), and hydration (water balance). The final factor is clothing. In terms of heat exchange, clothing physically modifies the rate of heat exchange between the body and the environment. Chemical protective clothing is evaluated by measuring the properties of clothing that are biologically significant and by measuring the physiological differences in subject responses when the external environment is controlled.

## 3. Clothing

To design CP clothing that maintains an adequate level of chemical protection while reducing the level of heat strain experienced by the users requires the resolution of a paradox: good chemical protection is synonymous with poor heat exchange properties. Chemical protective clothing is specifically designed to minimize pumping and ventilation, the exchange of air between the outside environment and the air space layers inside the clothing, by sealing the openings at the neck, waist and cuffs of the zipped uniform so that specific agents cannot reach the skin surface. Body surfaces that would normally permit effective heat exchange, such as the face and hands, are also covered. The net amount of heat exchange that occurs directly between the skin surface and the environment may be affected by how the garment is designed and worn. In MOPP-0 to MOPP-2, the face and hands are exposed and air moves through the neck and wrist openings, whereas in MOPP-4, the face and hands are covered, and there is no air exchange between air inside the clothing and the external environment.

Two clothing properties, insulation and water vapor permeability, modify the rate of thermal exchange from the body surface through the clothing to the external environment. In terms of heat exchange, greater insulation and reduced water vapor permeability will reduce the rate of heat exchange and may cause an increase in body temperature. Usually "heavier" clothing is associated with an increase in insulation and a reduction in water vapor permeability. Insulation is a term for the combined resistance to convective and radiative

heat exchange through the clothing. Under certain circumstances, when external air temperature ($T_a$) exceeds mean skin temperature ($\bar{T}_{sk}$), or there is a very high external radiant source, the body will gain heat from the environment. Under those circumstances, greater clothing insulation is advantageous. In general, military CP clothing may be "improved" by adjusting the properties of insulation and water vapor permeability. A more complete discussion of how clothing properties impact heat exchange, including CP clothing, is presented elsewhere (9,11,22).

When clothing is made of similar materials, generally "heavier" clothing indicates an increase in weight, bulk and insulation. However, using different materials can alter the relationship between these three factors. Insulation and water vapor permeability are usually more closely related to clothing thickness (bulk) than weight per se. Down and synthetic batting can increase bulk and insulation without increasing weight. A more open weave fabric may reduce weight, but maintain bulk and insulation. Highly reflective outer surfaces can reduce radiative heat gain without significantly impacting either weight or bulk, but a shiny surface is not practical for military clothing. Another important consideration is that convective heat loss is determined in part by the thickness of air layers trapped between surfaces or at the outer clothing surface. Clothing of the same cut but differing thickness may still tend to trap the same amount of air within, on and between heat exchange surfaces. In other words, lighter weight does not necessary translate into a significantly different rate of heat exchange. Furthermore, at protective levels of MOPP-2 or less, there is significantly more exposed skin surface and more direct exchange of air between clothing spaces and the external environment. Under those circumstances, the importance of heat exchange rates through clothing, and any differences in clothing materials, is also reduced.

During this study, by necessity, no information was provided to the investigators concerning clothing properties. Differences in clothing weight could be determined from comparisons of issue and prototype pre-test clothed weights, but no information was available regarding clothing insulation or water vapor permeability. Specifications for test prototypes were controlled at the time of this study, so there was insufficient information to place the prototypes within the general context of clothing properties, other than an anticipated 40% weight reduction for the prototype garments.

The two types of CP garments included in this study demonstrate alternative approaches to CP. The undergarment system (CPU) is intended for continuous, full-time wear, whereas the CP overgarment (CPO) is donned only in response to an anticipated threat. The trade-off between the two strategies for chemical protection may be a higher state of readiness at a cost of an increased potential for thermal stress, perhaps bulkier clothing for CP underwear versus a longer response to a chemical threat, but less of a thermal and physical burden when the overgarment is not worn.

The weight and relative bulk of CP garments may also have a thermal impact due to impedance, the so-called "hobbling effect" that reduces the efficiency of movement, thereby increasing the metabolic cost of an activity. Other factors, such as level of chemical protection, cost, and durability are also important considerations in the final selection of CP

garments, but these factors do not impact the thermal burden (heat load) imposed by CP garments.

Many factors influence the selection of CP clothing. A CP garment that provides improved heat exchange properties, but fails to provide protection from chemical or biological agents is clearly unacceptable. The biophysical evaluation of clothing conducted at USARIEM encompasses only physiological responses to heat stress and the thermal properties of the clothing. The final selection of a CP garment is dependent on all the relevant properties of the available prototypes. Other factors (chemical protection, cost, and durability) are also considerations in the final selection of CP garments, but these factors do not impact the thermal burden (heat load) imposed by CP garments.

# II. METHODS AND MATERIALS

## A. GENERAL

Test methods followed those developed for The Technical Cooperative Program (TTCP) program (10). These CP garment tests considered only the relative efficacy of the garments as opposed to a complete evaluation of the total CP system in MOPP-4 configuration. Volunteers were heat acclimated for 6 days by walking on level treadmills at 1.56 $m \cdot s^{-1}$ (3.5 mph) with environmental test chamber conditions at 49°C (120°F), 20% rh and 1.1 $m \cdot s^{-1}$ (2.5 mph) wind speed. For garment testing, the basic test procedure was to alternately dress test volunteers in the standard issue (control) garment or the prototype CP ensemble and expose the volunteers to a fixed set of environmental conditions. One control CP ensemble was the USMC Saratoga overgarment worn over underwear, and the other control ensemble consisted of the CPU worn under the U.S. Army Battledress uniform (BDU). The BDU was worn as part of the undergarment CP ensemble, but overgarments were worn, without a BDU, over underwear. All CP ensembles were worn in a modified MOPP-1 configuration with the integral hood up and CP gloves, but no CP mask or CP overboots. On garment test days, the volunteers entered the test chamber, stood for a 10 minute baseline, then began walking on level treadmills at 1.34 $m \cdot s^{-1}$ (3 mph) for a maximum of 100 min. Test environments were Temperate (20°C, 50% RH), Desert (49°C, 20% RH) and Tropic (35°C, 75% RH). The wind speed for all environments was 1.1 $m \cdot s^{-1}$ (2.5 mph). Volunteers did not drink water during the chamber testing. Seven male volunteer test subjects were recruited from the SSCOM Test Volunteer Platoon. Testing was conducted in the Doriot Environmental Chamber Building. With three environments and four clothing treatments, the basic test matrix required 12 days in addition to the 6 days required for acclimation. Independent parameters were air temperature and garment type. Dependent parameters were rectal temperature ($T_{re}$), three point mean skin temperature ($\bar{T}_{sk}$), and exposure or tolerance times (ET).

## B. TESTING

### 1. Test Schedule

The test schedule was divided into blocks based on the CP clothing treatment. The issue and prototype CPU were tested in all three environments as one block, and the CPO garments in the same environments were tested in the second block. A complete test series consisted of acclimation, a CPU block and a CPO block. Presentations of treatments were counterbalanced within each block. The test schedule is presented in Table 1. With three environments and four clothing treatments, the test matrix required 12 days.

| TABLE 1. Test Schedule | | | | |
|---|---|---|---|---|
| Acclimation Period Days 1-6 | | | | |
| Test Block 1 Days 7-12 | | | | |
| Subjects | 1 - 2 | 3 - 4 | 5 - 6 | 7 |
| Garment Type | CPU | | CPO | |
| ENV 3 - Tropic | PROTO-X | ISSUE-C | ISSUE-C | PROTO-X |
| ENV 1 - Desert | ISSUE-C | PROTO-X | PROTO-X | ISSUE-C |
| ENV 2 - Temperate | PROTO-X | ISSUE-C | ISSUE-C | PROTO-X |
| ENV 3 - Tropic | ISSUE-C | PROTO-X | PROTO-X | ISSUE-C |
| ENV 1 - Desert | PROTO-X | ISSUE-C | ISSUE-C | PROTO-X |
| ENV 2 - Temperate | ISSUE-C | PROTO-X | PROTO-X | ISSUE-C |
| Test Block 2 Days 13-18 | | | | |
| Subjects | 1 - 2 | 3 - 4 | 5 - 6 | 7 |
| Garment Type | CPO | | CPU | |
| ENV 1 - Tropic | ISSUE-X | PROTO-X | PROTO-X | ISSUE-C |
| ENV 2 - Desert | PROTO-C | ISSUE-C | ISSUE-C | PROTO-X |
| ENV 3 - Temperate | ISSUE-X | PROTO-X | PROTO-X | ISSUE-C |
| ENV 1 - Tropic | PROTO-C | ISSUE-C | ISSUE-C | PROTO-X |
| ENV 2 - Desert | ISSUE-X | PROTO-X | PROTO-X | ISSUE-C |
| ENV 3 - Temperate | PROTO-C | ISSUE-C | ISSUE-C | PROTO-X |

## 2. Acclimation

Volunteers were heat acclimated for 6 days prior to MOPP-1 garment testing by walking on a level treadmill at 1.56 $m \cdot s^{-1}$ (3.5 mph) with environmental test chamber conditions at 49°C (120°F), 20% rh and 1.1 $m \cdot s^{-1}$ wind speed. Their 120 minute exposure was divided into a 10 minute standing baseline, and two 50 minute walk sessions separated by a 10 minute rest period. Water was provided ad libitum. Acclimation methods were derived from Pandolf et al. (20). The subjects wore gym shorts and running shoes during acclimation. Heart rate and rectal temperature were monitored during acclimation. There was a 1-day break between acclimation and the start of garment testing.

## 3. Clothing

The two types of CP garments included in this study demonstrate alternative approaches to CP clothing. The undergarment system (CPU) is for continuous, full-time wear, whereas the CP overgarment (CPO) is donned only in response to an anticipated threat. The modified MOPP-1 configuration used for this study was chosen to separate the thermal impact of the clothing from mask effects. The CP overboots were eliminated primarily as a safety concern. The impact of overboots on overall heat exchange is minor when leather combat boots are worn.

## 4. Pre-Test

On test days, after reporting to the dressing area, volunteers were given 400 ml of water to drink prior to their initial nude weigh-in. Then they were instrumented and dressed for the test session. Subject instrumentation consisted of a chest band heart-rate monitor with a wrist-mounted display, a rectal temperature thermistor and three heat flow sensors (chest, forearm and calf). Prior to entering the test chamber, all subjects were weighed fully clothed, and there was an instrument function check.

## 5. Chamber Testing

The three environments were at air temperatures and humidities of 20°C (68°F), 50% RH; 49°C (120°F), 20% RH; and 35°C (95°F), 75% RH, respectively, for thermoneutral, Desert and Tropic environments. The simulated wind speed for both environments was minimal, at 1.1 $m \cdot s^{-1}$. Volunteers entered the test chamber, and their instrument leads were connected to the data acquisition system. The 10 minute baseline began when the subjects are connected to the Data Acquisition (DA) system and the first complete set of temperatures were displayed. After connection to DA system, the volunteers remained standing in place for 10 minutes to establish a data baseline. The subjects were not allowed to drink during testing or until their final nude weight was obtained. Subjects walked continuously on the treadmill at 1.34 $m \cdot s^{-1}$ until they completed 100 minutes of walking, voluntarily withdrew from the test session, or were withdrawn by the test staff and/or medical monitor. Criteria for removal of volunteers by test observers included instrument readings at the specified physiological limits for heart rate and rectal or surface temperatures, signs of acute heat stress such as headaches, nausea, dizziness, disorientation, or other indications of extreme discomfort or pain.

## 6. Post-Test Measurements

Volunteers exited the test chamber and were weighed fully clothed. After removal of all clothing and instrumentation, their nude weights were also measured and recorded. Subject then completed a questionnaire regarding their subjective response to the test garment worn that day [Hennessy (personal communications)].

## C. HEALTH AND SAFETY OF TEST VOLUNTEERS

Seven male volunteers were recruited for participation from the SSCOM Test Volunteer Platoon. They were fully informed by a verbal presentation regarding the test methods and safety concerns and then signed a written consent form indicating their freely given consent to participate in the study. Volunteers receive a complete physical examination, and were screened for a prior history of heat injury. The procedures for this study conformed to the limits specified in the USARIEM Type Protocol for Human Research Studies of Thermal Stress (27). Rectal temperatures were not allowed to exceed 39°C, and volunteers could not sustain a heart rate greater than 90% of the maximum heart rate for more than 5 minutes. Maximum heart rate was calculated according to the age-based equation specified in the USARIEM type protocol. Volunteers were allowed to voluntarily remove themselves from testing prior to reaching their specified physiological limits. The medical monitor and/or the test observers could also remove a volunteer based on verbal or symptomatic indications of impending illness.

# III. RESULTS

## A. GENERAL OBSERVATIONS

Figures 1-3 illustrate ET by garment type for each environment. Figure 4 presents $\Delta T_{re}$ values for one subject in the 20°C Temperate environment. Note that values tend toward equilibrium. Mean values (with standard deviations) for dependent variables are summarized in Tables 2-3. In the following tables and discussion, "O" refers to an overgarment or CPO, "U" refers to an undergarment or CPU, "C" indicates an issue or control garment and "X" refers to a prototype or experimental garment. The basic key is OC = issue or Saratoga CPO, OX = prototype CPO, UC = issue CPU, UX = prototype CPU.

Figure 1. Endurance times (ET in minutes) for all garments in the Tropic environment

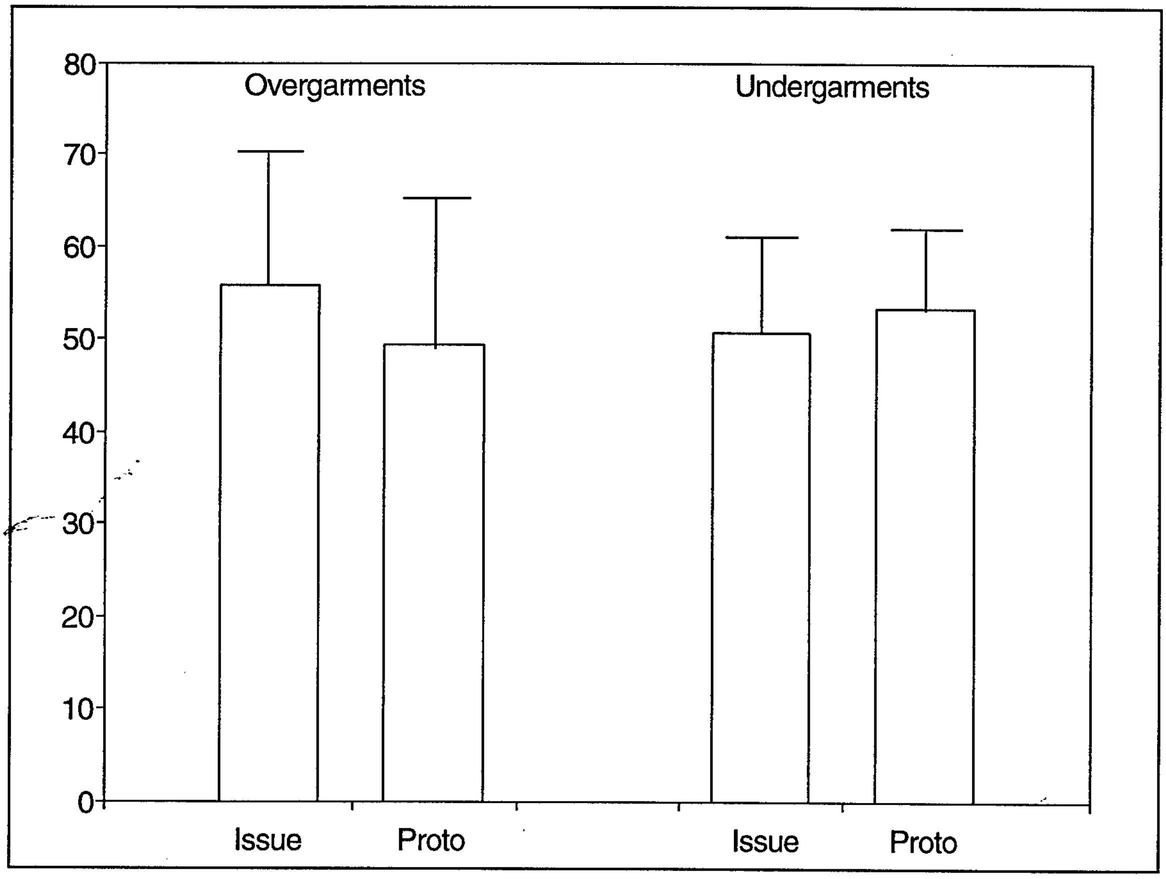


Figure 2. Endurance times (ET in minutes) for all garments in the Desert environment

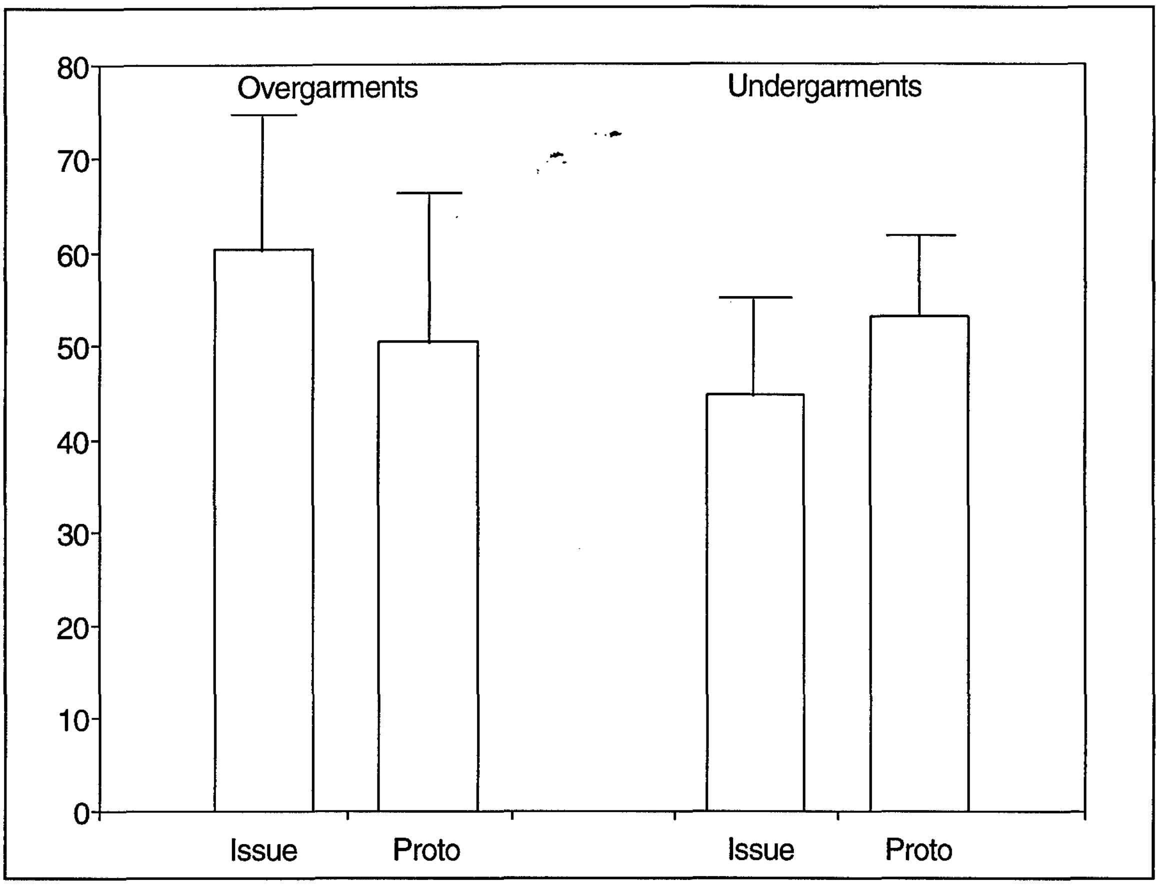


Figure 3. Endurance times (ET in minutes) for all garments in the Temperate environment

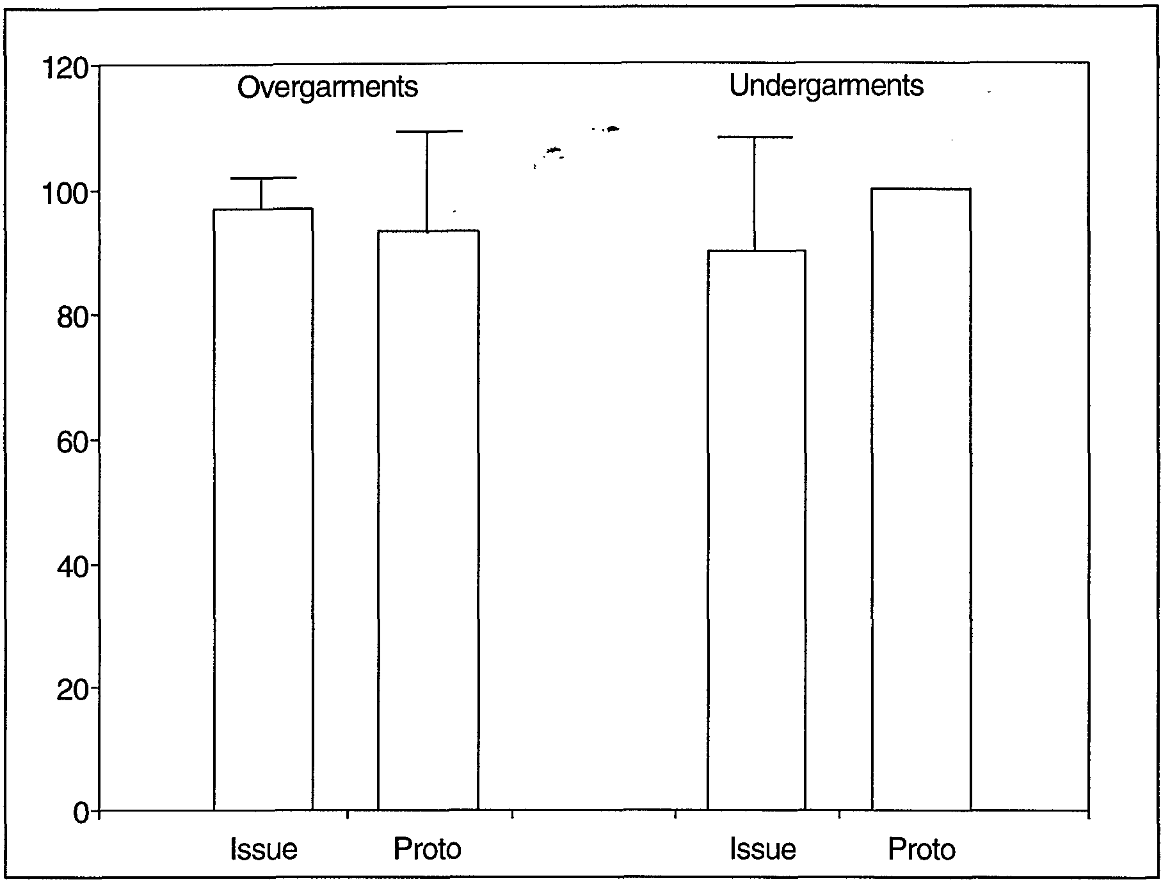
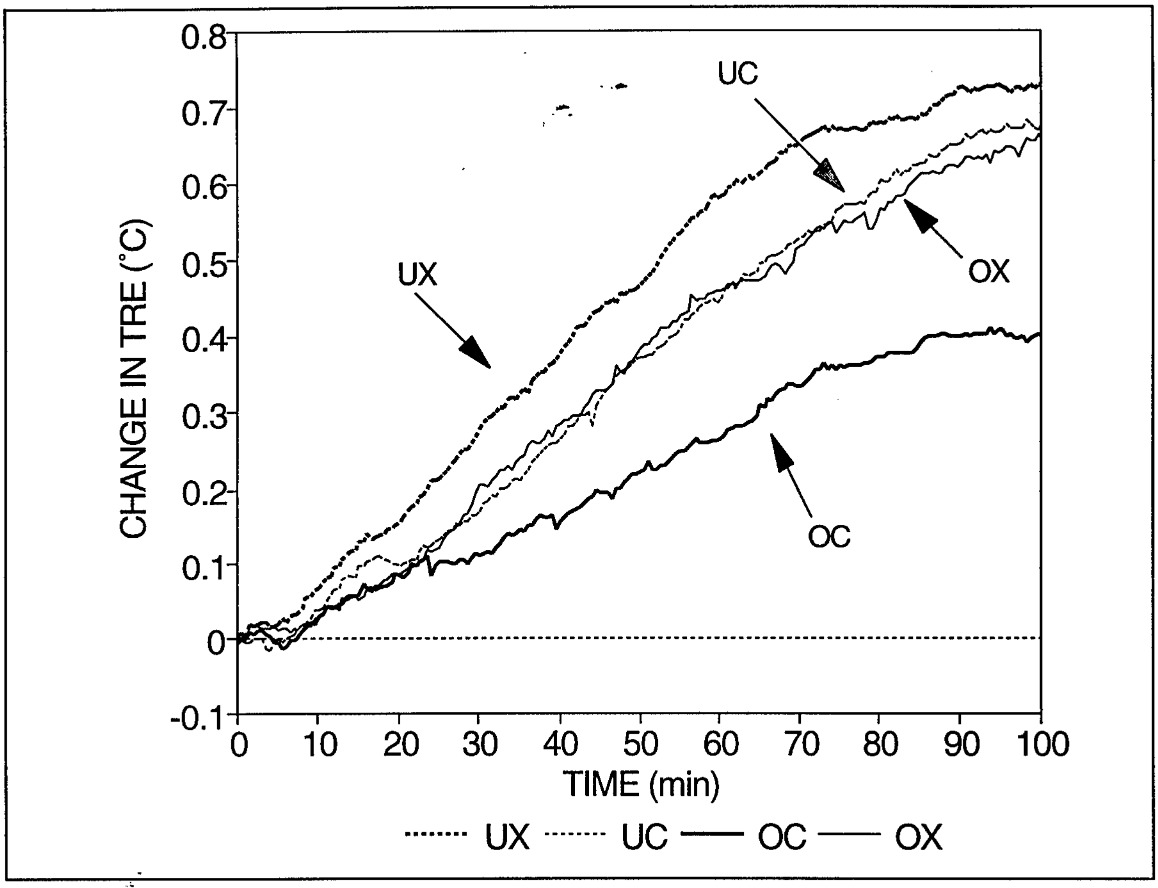


Figure 4. Representative change in rectal temperature ($T_{re}$) for all garments in the Temperate environment (one subject)




## B. STATISTICS

### 1. Descriptive Statistics

**a. Variables**. The independent variables were environment and garment type. Dependent variables generated were endurance time (ET), final $T_{re}$, final mean skin temperature ($\bar{T}_{sk}$), final mean body temperature ($\bar{T}_b$), the rate of change in those three temperatures ($\Delta T_{re}$, $\Delta \bar{T}_{sk}$, $\Delta \bar{T}_b$), the rate of sweat loss (SWL), the evaporative water loss (EL), and the cooling efficiency (EFF) of water loss.

Temperature Rates of Change: In the Temperate, 20°C environment, body temperatures were approaching equilibrium for most tests. A rate-of-change calculation that assumes a linear non-equilibrium increase in body temperatures is inappropriate. Hence, those variables ($\Delta T_{re}$, $\Delta \bar{T}_{sk}$ and $\Delta \bar{T}_b$) were not used for the 20°C environment. $\bar{T}_b$ was calculated using two equations that weighted the relative contributions of $T_{re}$ and $\bar{T}_{sk}$ in different ratios. Due to body mass, there is a delay or lag between the onset of an activity or exposure and a change in $T_{re}$. To capture the linear phase of the increase in body temperature, the initialization point was set at either 15 or 20 minutes after the onset of walking. In hot environments, an equations that weights $T_{re}$ more heavily is usually preferred:

$$\bar{T}_b = 0.9 \cdot T_{re} + 0.1 \cdot \bar{T}_{sk}$$

When sweating is an important factor, the cooling of the skin may make an important contribution, and an equation that increases the weight of $\bar{T}_{sk}$ may be more appropriate:

$$\bar{T}_b = 0.8 \cdot T_{re} + 0.2 \cdot \bar{T}_{sk}$$

**b. Water Loss**. The water loss values were calculated using three different assumptions. One method (wEL and wSWL) assumed that all water losses occur only during the walking (ET) time. The second method (cEL, cSWL) assumed that some water loss also occurred prior to the onset of walking, so the time period included the 10-min chamber baseline period (ET+10). The third method (sEL, sSWL) was to standardize the data for body size. The Dubois surface area ($A_{DU}$) was calculated for each subject from their height and daily mean weight (pre- and post-test nude weights). The cEL and cSWL values were divided by the individual $A_{DU}$ values, then multiplied by the mean $A_{DU}$ for the group, which was 1.90 $m^2$. With the exception of wEL in the 20°C (68°F) environment, the differences between the three approaches to EL and SWL were only in the degree of variability (SD). In general, wEL and wSWL demonstrated larger variance than the cEL, sEL, etc., variables.

**c. Tables**. Descriptive statistics (mean and standard deviation) were generated for each variable (Table 2-3). Data for changes in temperature ($\Delta T_{re}$, $\Delta \bar{T}_{sk}$, $\Delta \bar{T}_b$) are based on a 20 min lag time. For $\Delta \bar{T}_b$, data calculated using the equation that placed more weight ($0.2 \cdot \bar{T}_{sk}$) on skin temperature are presented in Table 2. The rationale for these selections were based on a combination of smaller SDs and/or more favorable statistical analysis.

## 2. Statistical Analysis

Statistical analysis was repeated using two methods for grouping data (Tables 4-6). One method was to pool the data for all four garment treatments. Then an Analysis of Variance (ANOVA) with repeated measures was applied to the pooled data set (SAS). The ANOVA provides an indication of overall significance for each variable, but does not indicate which differences between pairs within the data set are significant. A Tukey's Studentized Range Test (0.05 level of significance) is then applied to all pairs for variable data sets that have overall significance. The second method, paired t-tests, treated each pair of treatments, overgarment (OC and OX) and undergarments (UC and UX), as discrete blocks. For the second method, there are only two sets of data per variable. Consequently, there is no need to perform a second test (Tukey's) to determine significance between treatments. The first method provides more information by indicating if there is a significant difference between undergarments and overgarments, but the second method is more appropriate when the tests were divided into undergarment and overgarment blocks.

| Table 2. Time and temperature data | | | | | | | |
|---|---|---|---|---|---|---|---|
| CP Garment | ET min | $T_{re}$ (F) °C | $\bar{T}_{sk}$ (F) °C | $\bar{T}_b$ (F) °C | $\Delta T_{re}$ (20) $°C \cdot h^{-1}$ | $\Delta \bar{T}_{sk}$ (20) $°C \cdot h^{-1}$ | $\Delta \bar{T}_b$ (20) $°C \cdot h^{-1}$ |
| Tropic (95°F, 75% RH, 2.5 mph wind) | | | | | | | |
| CPO-C | 55.8 (14.7) | 38.49 (0.50) | 37.00 (0.32) | 38.20 (0.45) | 2.07 (0.40) | 0.39 (0.46) | 1.74 (0.35) |
| CPO-X | 49.4 (12.2) | 38.33 (0.51) | 37.03 (0.39) | 38.07 (0.48) | 2.00 (0.33) | 0.74 (0.65) | 1.75 (0.29) |
| CPU-C | 50.6 (10.6) | 38.57 (0.44) | 37.66 (0.43) | 38.39 (0.43) | 2.39 (0.36) | 1.23 (0.54) | 2.15 (0.30) |
| CPU-X | 53.4 (10.0) | 38.48 (0.44) | 37.11 (0.25) | 38.21 (0.39) | 2.13 (0.37) | 0.63 (0.29) | 1.83 (0.32) |
| Desert (120°F, 20% RH, 2.5 mph wind) | | | | | | | |
| CPO-C | 60.4 (14.5) | 38.49 (0.39) | 37.13 (0.37) | 38.22 (0.36) | 1.92 (0.28) | 0.01 (1.14) | 1.54 (0.36) |
| CPO-X | 50.5 (15.8) | 38.27 (0.47) | 36.84 (0.74) | 37.98 (0.51) | 1.97 (0.49) | -1.06 (2.22) | 1.37 (0.49) |
| CPU-C | 44.7 (10.5) | 38.31 (0.39) | 37.58 (0.35) | 38.16 (0.37) | 2.40 (0.41) | 0.86 (0.68) | 2.10 (0.40) |
| CPU-X | 53.1 (8.6) | 38.53 (0.38) | 37.21 (0.38) | 38.27 (0.36) | 2.28 (0.40) | 0.23 (0.59) | 1.87 (0.37) |
| Temperate (68°F, 50% RH, 2.5 mph wind) | | | | | | | |
| CPO-C | 97 (5) | 37.62 (0.22) | 32.05 (1.09) | 36.51 (0.28) | 0.30 (0.10) | -0.93 (0.82) | 0.05 (0.16) |
| CPO-X | 93 (16) | 37.61 (0.21) | 32.32 (0.65) | 36.55 (0.17) | 0.30 (0.10) | -0.86 (0.46) | 0.07 (0.15) |
| CPU-C | 90 (18) | 37.54 (0.15) | 33.22 (0.57) | 37.10 (0.12) | 0.43 (0.21) | -0.65 (0.51) | 0.21 (0.24) |
| CPU-X | 100 (0) | 37.66 (0.21) | 32.53 (0.21) | 37.15 (0.17) | 0.39 (0.13) | -0.82 (0.46) | 0.15 (0.17) |

| Table 3. Water loss data | | | | | | | |
|---|---|---|---|---|---|---|---|
| CP Garment | cEL $g \cdot min^{-1}$ | cSWL $g \cdot min^{-1}$ | EFF % | sEL $g \cdot min^{-1}$ | sSWL $g \cdot min^{-1}$ | wEL $g \cdot min^{-1}$ | wSWL $g \cdot min^{-1}$ |
| Tropic (95°F, 75% RH, 2.5 mph wind) | | | | | | | |
| CPO-C | 2.55 (1.30) | 22.85 (4.22) | 11.7 (7.3) | 2.58 (1.31) | 23.06 (4.96) | 2.99 (1.50) | 27.22 (5.23) |
| CPO-X | 2.79 (1.25) | 23.59 (5.57) | 11.8 (5.1) | 2.75 (1.21) | 23.67 (5.82) | 3.35 (1.46) | 28.63 (6.74) |
| CPU-C | 2.95 (1.66) | 26.07 (6.56) | 11.4 (5.9) | 2.86 (1.45) | 26.08 (6.18) | 3.53 (2.01) | 31.49 (8.26) |
| CPU-X | 3.20 (0.73) | 23.21 (3.67) | 13.9 (3.3) | 3.18 (0.61) | 23.34 (4.22) | 3.81 (0.87) | 27.70 (4.55) |
| Desert (120°F, 20% RH, 2.5 mph wind) | | | | | | | |
| CPO-C | 9.65 (1.90) | 23.26 (5.08) | 42.2 (8.3) | 9.61 (1.78) | 23.26 (4.93) | 11.27 (1.87) | 27.31 (5.67) |
| CPO-X | 9.19 (1.70) | 24.51 (5.18) | 38.8 (9.5) | 9.16 (1.14) | 24.78 (6.09) | 11.15 (2.09) | 29.98 (7.47) |
| CPU-C | 7.55 (1.62) | 25.96 (5.29) | 29.6 (6.7) | 7.51 (1.41) | 26.10 (5.96) | 9.28 (1.91) | 32.00 (6.63) |
| CPU-X | 8.96 (1.91) | 25.28 (5.56) | 36.0 (6.3) | 8.90 (1.40) | 25.26 (4.85) | 10.69 (2.30) | 30.18 (6.67) |
| Temperate (68°F, 50% RH, 2.5 mph wind) | | | | | | | |
| CPO-C | 4.10 (0.79) | 6.89 (1.72) | 60.5 (8.9) | 4.07 (0.61) | 6.87 (1.64) | 4.51 (0.86) | 7.60 (1.91) |
| CPO-X | 4.68 (0.81) | 8.07 (1.88) | 58.8 (5.0) | 4.68 (0.62) | 8.08 (1.73) | 5.20 (0.89) | 8.98 (2.11) |
| CPU-C | 4.23 (1.23) | 8.06 (2.67) | 53.8 (12.2) | 4.17 (0.99) | 8.00 (2.56) | 4.70 (1.32) | 9.00 (3.07) |
| CPU-X | 4.28 (0.77) | 7.28 (1.55) | 59.7 (9.6) | 4.24 (0.51) | 7.27 (1.51) | 4.70 (0.85) | 8.01 (1.70) |

## 3. Statistical Inferences

In the 49°C (120°F, Table 5) environment, garment insulation "protects" subjects from convective heat gain. The advantage of greater insulation may, however, be offset by a reduction in water vapor permeability. The results for the Desert environment indicate that the issue CPU (UC) is significantly different (worse) than the prototype CPU (UX), issue CPO (OC) and the prototype CPO (OX) for most test variables. The prototype undergarment (UX) is significantly different (worse) than OC and OX in terms of the rate of increase in body temperature ($\Delta T_{re}$, $\Delta \bar{T}_b$). There were no significant differences between the two CPO garments.

In the 35°C (95°F, Table 4) environment, the temperature difference between the body and the environment is small, and environmental conditions limit the effectiveness of evaporative water loss. When the mean sweat loss rates (cSWL) for 35° and 49°C for all four garments are compared, 23.93 vs. 24.75 $g \cdot min^{-1}$, there is little apparent difference between the Tropic and Desert environments. But for evaporative loss (cEL), the difference between 35° and 49°C is 2.87 vs. 8.84 $g \cdot min^{-1}$. This is also reflected by the difference in evaporative efficiency (EFF) which is 12.2% for 35°C vs. 36.6% for 49°C. Despite the inefficiency of sweating to cool the body, the rate of sweat loss may be significant because it correlates to the overall level of thermal strain ($\Delta T_{re}$, $\Delta \bar{T}_b$). Statistical results indicate that the prototype CPU (UX) is significantly better than the issue CPU (UC) and, for some variables, the issue CPU (UC) garment was significantly worse then the CPO type of garment. There was no significant difference between CPO garments or between the CPO garments and UX.

In the 20°C (68°F, Table 6) environment, values for the rate of change in body temperatures were calculated and analyzed, but given that the body temperatures tend towards an equilibrium, the validity of assuming a linear increase in core temperature parameters is untenable. The majority of parameters which were statistically significant in the Temperate environment were for sweat rate (SWL) evaporative water loss (EL). In a thermoneutral, temperate environment, greater evaporative water loss would be an advantage at higher metabolic rates and/or for the perception of comfort. The OX garment demonstrated a higher rate of evaporative water loss (EL) than the OC. There was also a significant difference between OX and UC for the walk-only (wEL) version of the EL variable.

Collectively the data indicate a ranking of the CP garments of OX and OC, then UX and finally UC in descending order of overall performance. There was relatively little data that supported any significant differences between the two overgarments, except for the evaporative water loss at 20°C. The difference in ET for the CPO garments, although not statistically significant, provides limited support for the opposite conclusion, that OC is a better garment than OX. However, that difference in ET may reflect non-thermal factors, such as comfort, fabric stiffness or fit. Another indicator that OC may actually be better than OX is that the number of significant cases (Tukey's) between OC and the two CPU garments is greater than the number of significant cases between OX and the CPU garments. Hennessy (personal communications) has indicated that his questionnaire results for the volunteers' subjective preferences were also not significant, but his descriptive statistics may lend support to the data interpretations in this report. There was considerable statistical

Table 4. Tropic (95°F) environment - Significant differences

| Pairings | UC - UX | OC - OX | UC - OC | UC - OX | UX - OC | UX - OX |
|---|---|---|---|---|---|---|
| Variable | Significance findings | | | | | |
| $\bar{T}_{sk}$ (final) | Tukey's (0.05) (p<0.0057) | NS | Tukey's (0.05) | Tukey's (0.05) | NS | NS |
| $\Delta T_{re}$ (15) | NS **(p<0.0642)** | NS | Tukey's (0.05) | Tukey's (0.05) | NS | NS |
| $\Delta\bar{T}_{sk}$ (15) | Tukey's (0.05) (p<0.0135) | NS | Tukey's (0.05) | NS | NS | NS |
| $\Delta\bar{T}_{b}$ (15) | Tukey's (0.05) (p<0.0197) | NS | Tukey's (0.05) | Tukey's (0.05) | NS | NS |
| $\Delta T_{re}$ (20) | Tukey's (0.05) (p<0.0217) | NS | Tukey's (0.05) | Tukey's (0.05) | NS | NS |
| $\Delta\bar{T}_{sk}$ (20) | Tukey's (0.05) (p<0.0112) | NS | Tukey's (0.05) | NS | NS | NS |
| $\Delta\bar{T}_{b}$ (20) | Tukey's (0.05) (p<0.0088) | NS | Tukey's (0.05) | Tukey's (0.05) | NS | NS |
| cSWL | NS **(p<0.0734)** | NS | Tukey's (0.05) | NS | NS | NS |
| sSWL | NS **(p<0.0600)** | NS | Tukey's (0.05) | NS | NS | NS |
| wSWL | Tukey's (0.05) **(p<0.0602)** | NS | Tukey's (0.05) | NS | NS | NS |

OC = ISSUE CPO OX = PROTOTYPE CPO UC = ISSUE CPU UX = PROTOTYPE CPU
p values are for paired-t tests, **boldface** indicates a value greater than the 0.05 level of significance

Table 5. Desert (120°F) environment - significant differences

| Pairings | UC - UX | OC - OX | UC - OC | UC - OX | UX - OC | UX - OX |
|---|---|---|---|---|---|---|
| Variable | Significance for garment pair | | | | | |
| $\bar{T}_{sk}$ (final) | $p<0.0362$ | NS | NS | Tukey's (0.05) | NS | NS |
| $\Delta T_{re}$ (15) | NS | NS | Tukey's (0.05) | Tukey's (0.05) | Tukey's (0.05) | NS |
| $\Delta \bar{T}_{sk}$ (15) | $p<0.0335$ | NS | NS | Tukey's (0.05) | NS | NS |
| $\Delta \bar{T}_{b}$ (15) | NS | NS | Tukey's (0.05) | Tukey's (0.05) | Tukey's (0.05) | Tukey's (0.05) |
| $\Delta T_{re}$ (20) | NS | NS | Tukey's (0.05) | Tukey's (0.05) | Tukey's (0.05) | Tukey's (0.05) |
| $\Delta \bar{T}_{sk}$ (20) | **$p<0.0561$** | NS | NS | Tukey's (0.05) | NS | NS |
| $\Delta \bar{T}_{b}$ (20) | NS | NS | Tukey's (0.05) | Tukey's (0.05) | NS | Tukey's (0.05) |
| ET | $p<0.0430$ | NS | Tukey's (0.05) | NS | NS | NS |
| EFF | $p<0.0002$ | NS | Tukey's (0.05) | Tukey's (0.05) | NS | NS |
| cEL | $p<0.0489$ | NS | Tukey's (0.05) | Tukey's (0.05) | NS | NS |
| sEL | $p<0.0416$ | NS | Tukey's (0.05) | Tukey's (0.05) | NS | NS |
| wEL | NS | NS | Tukey's (0.05) | NS | NS | NS |

OC = ISSUE CPO  OX = PROTOTYPE CPO  UC = ISSUE CPU  UX = PROTOTYPE CPU
p values are for paired-t tests, **boldface** indicates a value greater than the 0.05 level of significance

Table 6. Temperate (68°F) environment - significant differences

| Pairings | UC - UX | OC - OX | UC - OC | UC - OX | UX - OC | UX - OX |
|---|---|---|---|---|---|---|
| Variable | Significance for garment pair | | | | | |
| $\bar{T}_{sk}$ (final) | **p<0.0531** | NS | NS | NS | NS | NS |
| cEL | NS | Tukey's (0.05)<br>p<0.0154 | NS | NS | NS | NS |
| cSWL | NS | **p<0.0623** | NS | NS | NS | NS |
| sEL | NS | Tukey's (0.05)<br>p<0.0203 | NS | NS | NS | NS |
| sSWL | NS | **p<0.0711** | NS | NS | NS | NS |
| wEL | NS | Tukey's (0.05)<br>p<0.0118 | NS | Tukey's (0.05) | NS | NS |
| wSWL | NS | **p<0.0788** | NS | NS | NS | NS |

OC = ISSUE CPO OX = PROTOTYPE CPO UC = ISSUE CPU UX = PROTOTYPE CPU
p values are for paired-t tests, **boldface** indicates a value greater than the 0.05 level of significance

support for a conclusion that the issue undergarment (UC) was significantly different (worse) than the two overgarments. When there were statistically significant differences between the undergarments, the prototype (UX) tended to perform better than the issue undergarment. In a few cases, all in the 49°C Desert environment, the prototype undergarment (UX) did significantly worse than the overgarments. Given that these data were for core temperatures, those differences should be given more weight than differences in parameters which account for only one factor that contributes to overall differences in body temperature.

To restate the basic argument for ranking the garments, generally, when there were significant differences, the two overgarments did better than the undergarments. Between the two undergarments, all significant differences indicated that the prototype (UX) would induce less thermal strain than the issue (UC) undergarment. The only significant differences between the two overgarments were found for a contributing factor (evaporative water loss) in the least stressful environment. However, there is insufficient evidence to suggest that the prototype (OX) overgarment is superior to the issue (OC) overgarment.

## IV. DISCUSSION

The developers of the prototype garments had anticipated a significant reduction in thermal strain and a corresponding increase in soldier endurance time. The relatively modest improvements were not the anticipated results. A statistically significant mean increase in endurance of 8 minutes, even though it is a 18% increase (Table 2 CPU-X vs. CPU-C in Desert) simply may not be very impressive when the various requisite costs of implementing a new clothing item are considered.

The test methods may have contributed to the impression that improvements attributable to the new garments were at best modest. As stated in the introduction, testing in MOPP-1 is not the best method to demonstrate the advantages of improved materials. The neck opening and exposure of the face allow considerable unimpeded heat exchange from the face surface and some "bellows" effect as air is exchanged through the neck openings. If heat transfer through clothing accounts for only 65% of heat exchange, a 20% improvement in that 65% may not translate into a large impact on soldier performance.

A factor which may have inflated performance expectations is the unreliable assumption that clothing weight and insulation are directly related. Counter examples are not difficult to find. Down insulation provides an unusually higher ratio of weight to insulation. In contrast, it is possible to use steel wool for insulation, but highly impractical due to the weight of the material. In addition neither the insulation of the surface air ($I_a$), approximately 0.3 clo, or the air layer trapped beneath the clothing are greatly modified by different clothing weights. A 40% decrease in clothing weight does not necessarily translate into a 40% reduction in thermal strain. A comparison of data from a biophysical manikin study would provide some indication of the potential for improvement provided by the new materials, but those data are not available.

The third factor which may have contributed to the modest performance of the prototype overgarment was the apparent stiffness of the material -- a factor in both comfort and actual impedance or the "hobbling effect." Attributing thermal costs to those material properties is highly speculative, and quite difficult to separate from other clothing properties. Ultimately, it is all the properties of a garment, weight, stiffness, insulation, water vapor permeability, fit, and even lining abrasiveness, that determine the relative performance of garments made from different materials. Differences between garments would be further reduced if the subjects had worn ballistic protection and/or load-bearing equipment (LBE) in a true "soldier system."

Product developers have expressed some frustration with the apparent futility of reducing heat strain. In part, there may be some confusion between reduction and elimination of heat strain and the differences between comfort, thermal comfort and heat strain. Even when a significantly improved garment is tested, subjects still complain of strain, and subjective responses (comfort questionnaires, etc) indicate no significant difference. This is not surprising given the fact that the Tropic and Desert test environments are uncomfortable even for a MOPP-0 condition without any CP garment.

The last significant change in CP clothing was the transition from impermeable garments, typified by earlier generation Soviet CP clothing (5), to the semi-permeable NBC garments almost universally issued by military forces today. It is unlikely that a major improvement in CP protective garments will be found by incorporating moderately improved materials in the same designs. Other approaches, such as the CPU concept and impregnating regular uniforms with protective properties (IDF), and improved micro-pore barriers with chemically active layers are at least novel. Unfortunately, thus far, the CPU and micro-pore garments have not been significantly more successful than the carbon-layer overgarments (16,22,23).

# V. SUMMARY

The two types of CP garments included in this study were the CPU and the CPO. The study compared the performance of seven male volunteers while wearing issue and lightweight prototype versions of the CP garments. A modified MOPP-1 configuration was used for testing to separate the thermal impact of the clothing from mask effects. The three test environments were at air temperatures and humidities of 20°C (68°F), 50% RH; 49°C (120°F), 20% RH; and 35°C (95°F), 75% RH, respectively, for thermoneutral, Desert and Tropic environments. The simulated wind speed for both environments was minimal, at 1.1 $m{\cdot}s^{-1}$. Subjects walked continuously on the treadmill at 1.34 $m{\cdot}s^{-1}$ for a maximum of 100 minutes of walking. Criteria for removal of volunteers by test observers included instrument readings at the specified physiological limits for heart rate and rectal temperatures, indicators of acute heat strain or other signs of extreme discomfort or pain. Subjects could also withdraw voluntarily from test sessions.

The results for the Desert (49°C) environment indicate that the issue CPU (UC) is significantly different (worse) than the prototype CPU (UX), issue CPO (OC) and the prototype CPO (OX) for many test variables. UX is significantly different (worse) than OC and OX in terms of the rate of increase in body temperature ($\Delta T_{re}$, $\Delta \bar{T}_b$). There was no significant difference between the two CPO garments. In the Tropic (35°C) environment, results were similar except that there were no significant differences between UX and the CPO garments. Most parameters which were statistically significant in the Temperate (20°C) environment were for water balance (SWL and EL). The prototype OX garment demonstrated a higher rate of evaporative water loss (EL) than the control OC. There was also a significant difference between OX and UC for the walk-only (wEL) version of the evaporative loss (EL) variable.

The data indicate a ranking of the CP garments of OX and OC, then UX and finally UC in descending order of overall performance. The only significant differences between the two overgarments were found for a contributing factor (evaporative water loss) in the least stressful environment. There was contradictory, and non-significant, data for endurance time (ET) that suggested that the issue OC overgarment was a more "wearable" garment than the OX prototype. Consequently, any thermal advantage of OX over OC is rather tenuous. The issue undergarment (UC) was significantly different (worse) than the two overgarments. In fewer cases (49°C), the prototype undergarment (UX) did significantly worse than the overgarments. Between the two undergarments, all significant differences indicated that the prototype (UX) would induce less thermal strain than the issue (UC) undergarment. When there were statistically significant differences between the undergarments, the prototype (UX) tended to perform better than the issue undergarment.

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